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Microbiological Improvement of the Physical Properties of Soil

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ABSTRACT

The application of microbiological processes for improvement of the physical properties of soils offers the promise of sustainable, cost effective, non-disruptive ground improvement for a variety of geotechnical problems. Potentially beneficial applications of microbiological processes include increasing the stiffness of soil to reduce settlement and lateral deformations, increasing shear strength to enhance foundation bearing capacity and slope stability and to facilitate excavation and tunneling, reducing the susceptibility of granular soil to earthquake-induced liquefaction, reducing swell (expansion) potential of fine grained soil, and reducing permeability for groundwater control. Microbiological processes that can potentially be employed for these applications include mineral precipitation, mineral transformation, and growth of biofilms and biopolymers. These processes are known to improve the engineering properties of soil on a geological time scale, and some of these processes are known to induce potentially beneficial effects in shorter time frames but in situations where the context renders the effects undesirable (e.g. clogging of water treatment plant filters). The engineering challenges in developing beneficial applications of these processes involve identifying the appropriate microbial processes to achieve the desired effect and inducing the desired process (or processes) over a time frame of engineering interest in the location of interest. If these challenges can be met, microbiological improvement of the physical properties of soil may transform some aspects of ground improvement in geotechnical practice.

INTRODUCTION

Leonardo Da Vinci was not only an artist but also a physicist, a mathematician, a biologist, a geologist, an architect, and an engineer. He was the proto-typical “Renaissance” man. His portfolio included the design of advanced combat devices and war vehicles, design of canals, churches, fortresses, studies on reflection of light, elements of mechanics, and, of course, his famous paintings. Yet, he found time to cut cadavers to study and sketch anatomy and physiology, regardless of the Pope’s interdiction. Of course, he wasn’t the only “Renaissance” man but one of the many that could qualify as scientist/engineer/artist. As technology advanced and our knowledge expanded from Leonardo’s time, scientists and engineers began to specialize in one area. In civil engineering, the period from 1930 to 1990 saw the development of geotechnical engineering as a distinct field of study in engineering mechanics and increasing specialization in the study of geo techniques. Developments in geotechnical engineering recent years such as the use of microorganisms for groundwater remediation and the use of Micro Electrical Mechanical Systems (MEMS) and nano-materials for sensors and sensing, have reversed this specialization trend, resulting in a “new” interdisciplinary approach to geotechnical engineering for integrating ideas and techniques from other disciplines to develop creative solutions to complex problems. The development of microbiological processes for improvement of the physical properties of soil is one of the more recent manifestations of this trend. This paper discusses several potential applications of microbiological improvement of soil properties to geotechnical engineering. It has been known for many years that microorganisms play significant roles in a number of important geological processes. Interactions between minerals and microorganisms have been studied extensively by microbiologists and geologists, though not by geotechnical engineers. This paper provides a brief background on relevant aspects of geomicrobiology, identifies several potential microbial mechanisms through which microbes could affect the physical properties of soils, and briefly discusses three potential beneficial applications associated with these mechanisms.

BACKGROUND

Geomicrobiology is the study of the role of microorganisms in geological processes and the interactions between minerals and microorganisms. It is an interdisciplinary science that requires understanding of microbial physiology, microbial ecology, geochemistry, and sedimentary geology. Microorganisms take part in reduction-oxidation (redox) reactions, gaining energy by reducing or oxidizing chemicals. One of the earliest geomicrobiologists, Winogradsky, in the second half of the 19th century discovered that the microbe *Beggiatoa* could oxidize elemental sulfur and that *Leptothrix ochracea* promoted oxidation of $FeCO_3$ to ferric oxide (Ehrlich, 2002). Subsequent researchers also found that not only do microorganisms partake in redox reactions but they may also precipitate and/or dissolve minerals, both directly and indirectly. A few years after Winogradsky's study, Nadson (1903) discovered that microbes play a role in calcium carbonate ($CaCO_3$) precipitation. The results of studies by Bryner *et al.* (1954) indicated that acidophilic (i.e., grows well in acidic medium) iron-oxidizing bacteria can promote the leaching of metals from various metal sulfide ores.

In recent years, bioremediation, the use of microbiological mechanisms to transform or immobilize environmental contaminants, has attracted a lot of attention in geoenvironmental engineering. Bioremediation has become an accepted remedy for soil and groundwater contaminated with hydrocarbons, especially with benzene, toluene, ethylbenzene, and xylene (BTEX). Bioremediation processes include natural attenuation, biostimulation, and bioaugmentation. Natural attenuation relies upon native microorganisms to degrade and transform contaminants. Monitored natural attenuation (MNA) has become the preferred remedy for soil and groundwater contaminated with many types of hydrocarbons, especially with BTEX contaminants. Biostimulation is a process in which environmental conditions are modified to enhance natural microbiological attenuation. Bioaugmentation is a process in which the subsurface environment is amended with exotic (i.e. non-native) microorganisms to degrade and/or immobilize harmful chemical constituents. Biostimulation is used in practice to remediate chlorinated hydrocarbons and other biostimulation and bioaugmentation remediation processes are now being implemented with increasing frequency.

Until recently, the application of microbiological processes to improve the mechanical properties of soil for engineering purposes (e.g., increasing shear strength, decreasing compressibility, decreasing hydraulic conductivity) remained largely unexplored, despite the role these processes play in many geologic and anthropogenic processes that are potentially beneficial. For instance, biochemically induced mineral precipitation is known to create cemented soils naturally on a geologic time frame but its potential to improve soil over a time frame of engineering interest has not been widely investigated. However, observations of clogging of filters and drainage media in dams, landfills, and at mine sites and the development of mineral "scale" in soil and on drainage pipes demonstrate that these phenomena can occur within a time frame of engineering interest. By harnessing geomicrobiological processes, we believe we can devise engineering solutions for temporary and/or permanent geotechnical engineering problems, including enhancing foundation bearing capacity, reducing susceptibility to earthquake-induced liquefaction, reducing the swell potential beneath foundations and roadways, enhancing slope stability, facilitating excavations and tunneling, and reducing permeability for groundwater control.

POTENTIAL MICROBIOLOGICAL IMPROVEMENT MECHANISMS

Mechanisms for potential applications of microbiology to geotechnical engineering can be divided into three main categories: mineral precipitation, mineral transformation, and biopolymer and biofilm accumulation. These mechanisms are described in this section of the paper. Examples of potential engineering applications of each one of these categories are presented in subsequent sections of this paper.

Mineral Precipitation

Microbially induced precipitation is recognized as the source of a wide variety of minerals in soils, including carbonates, oxides, phosphates, sulfides, and silicates (Fortin *et al.*, 1997). Carbonate precipitation is perhaps the earliest and most widely studied of this phenomenon (e.g., Nadson, 1903). Some microorganisms precipitate carbonate intracellularly and then export it to the cell surface (e.g., coccolithophores). However, many microorganisms induce carbonate precipitation extracellularly through metabolic processes that affect the geochemistry of the pore fluid, e.g increase alkalinity, pH, and/or the carbonate content.

Metabolic mechanisms can induce carbonate precipitation by increasing the total carbonate content or pH of the pore fluid, or by both mechanisms. Anaerobic and aerobic oxidation of an organic compound results in production of CO_2. If the medium is a well-buffered neutral or alkaline environment, CO_2 produced as a result of oxidation of an organic compound transforms into carbonate and then precipitates if there is an adequate amount of appropriate cations, such as Ca^{2+}. Precipitation is enhanced if the pH increases due to microbial production of alkalinity, which can occur in several ways. For instance, organic nitrogen may be released from organic compounds in the form of ammonia (NH_3). This includes organic nitrogen in urea, which releases NH_3 by ureolysis. Protonation of NH_3 generates alkalinity (OH^-) and leads to an increase in pH: $H_2O + NH_3 \rightarrow NH_4^+ + OH^-$ (Krumbein, 1979; Stocks-Fischer *et al.*, 1999; Fujita *et al.*, 2000; Hammes *et al.*, 2003; Whiffin, 2004). Also under anaerobic conditions, nitrate (NO_3^-) can be used as an electron acceptor by many bacteria (i.e., denitrification), producing N_2 gas, CO_2, and alkalinity: $NO_3^- + 1.25CH_2O \rightarrow 0.5N_2 + 1.25CO_2 + 0.75H_2O + OH^-$. Sulfate ($SO_4^{2-}$) can also be used as an electron acceptor under anaerobic conditions by microorganisms. In sulfate reduction, sulfate-reducing bacteria, such as *Desulfovibrio spp.* and *Desulfotomaculum spp.*, oxidize organic compounds while reducing sulfate to produce H_2S, CO_2, and alkalinity: $SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2CO_2 + 2OH^-$ (Abd-el Malik and Rizk, 1963a, 1963b). In landfills, methane formation from acetic acid adds CO_2 and removes the acidity of acetic acid while adding CO_2: $CH_3COOH \rightarrow CH_4 + CO_2$ (Brune *et al.*, 1991; Fleming *et al.*, 1999; Cooke *et al.*, 2001; Rowe *et al.*, 2002).

In addition to these mechanisms, Ehrlich (2002) lists "removal of CO_2 from bicarbonate containing solutions" as one of the microbial mechanisms that may lead to calcium carbonate precipitation. The most well-known process that may result in carbonate precipitation through this mechanism is oxygenic photosynthesis. In principle, all autotrophs (organisms that need CO_2 as source of carbon) may precipitate carbonate unless they generate acids (e.g., sulfide oxidizing bacteria, nitrifying bacteria). Moore (1983) reported that cyanobacteria and algae deposited calcareous nodules and crusts on subaqeous levees in the Flathead Lake delta in Montana. However, oxygenic photosynthesis is mainly dependent on light as source of energy, which limits the depth at which these microorganisms live. Because sunlight can only penetrate up to couple of millimeters below ground surface, oxygenic photosynthesis is only limited to the formation of soil crust. On the other hand, recently, a team of researchers discovered obligate photosynthetic green sulfur bacteria which live off the dim light coming from hydrothermal vents at nearly 2,400 m deep in the ocean (Beatty *et al.*, 2005). This discovery may compel researchers to reevaluate the limitations on photosynthesis within the subsoil ecosystem.

Mineral precipitation that results in a change in mechanical properties of soil can be used for permanent engineering applications. For instance, carbonate precipitation can result in cementation within soil with a potential increase in shear strength and a decrease in hydraulic conductivity and is known based upon geologic evidence to be long lasting. Ideally, based on the site characteristics, the optimal microbial mineral precipitation mechanism would be identified through a screening process and then applied in the field.

The effects of cementation on the shearing behavior of granular soils have been studied by many researchers (Sitar *et al.*, 1980; Bachus *et al.*, 1981; Abdulla and Kiousis, 1997; Fernandez and Santamarina, 2001; Asghari *et al.*, 2003; Haeri *et al.*, 2005; and Kasama *et al.*, 2006). Tests on artificially cemented soils indicate shear strength increases primarily due to an increase in cohesion, with only a slight increase in peak and residual internal friction angles for the cemented soil (Sitar *et al.*, 1980). Cementation with portland cement using as little as 2 percent cement by weight can result in a significant increase in cohesion, e.g. cohesion on the order of 45kPa for one sand (Sitar *et al.*, 1980). Tests conducted by Bachus *et al.* (1981) suggest that cementation can also increase the initial tangent modulus (i.e. increase the small strain stiffness) of a soil by up to an order of magnitude at low confining pressures, though the effect was much smaller at higher confining pressures. Based on the results of experiments with gypsum cemented gravelly sand, Haeri *et al.* (2005) reported that the friction angle of sand increases slightly due to cementation but that the increase in cohesion is more noticeable as the cement content increases. Fernandez and Santamarina (2001) reported that the small strain stiffness of sands can increase by an order of magnitude or more due to cementation. The results published by Fernandez and Santamarina (2001) indicate an increase in shear wave velocity (which is a function of small strain stiffness) of fine subangular sand from 230 m/s to 620 m/s at 100 kPa of confining pressure when mixed with 2 percent cement by weight before loading. These investigators also noted that cemented soils exhibit very limited changes in shear wave velocity due to stress change until de-cementation begins (Fernandez and Santamarina, 2001). However, all of these results are for abiotic cementation. Due to a difference in structure and organic content, microbially improved soils may display a different shearing and stiffness response than soils improved with abiotic cementation.

Successful development and implementation of microbial mineral precipitation mechanisms for soil improvement would have wide application to a variety of important geotechnical problems, including stabilization of slopes, control of soil erosion and scour, reducing under-seepage of levees and cut-off walls, increasing the bearing capacity of shallow foundations, excavation and tunneling in cohesionless soils, and remediation of seismic settlement and liquefaction potential. Microbial mineral precipitation may be especially useful near or beneath existing structures, where the application of traditional soil improvement techniques is limited because of associated ground deformations and/or high cost.

Mineral Transformation

Microbial mechanisms play an important role in weathering of minerals and the geologic cycle. For instance, some bacteria and fungi play an important role in mobilization of silica (Si) in nature (Ehrlich, 2002). Microbial metabolisms cause the mobilization of silica through solubilization by metabolically produced (a) complexing ligands, (b) acids, and (c) alkalinity. In addition, Kim *et al.* (2004) report that microorganisms can promote the transformation of smectite to illite through reduction of structural Fe(III) to Fe(II), which leads to potassium (K^+) uptake into the inter-layers. Smectite refers to a family of clay minerals composed primarily of hydrated sodium-calcium-aluminum silicate. Smectite minerals are the predominant cause of excessive swell (expansion) potential in soils. Illite refers to potassium-rich clay minerals that have much lower swell potential than smectite; the swell potential of illitic soils is not usually of engineering concern. Kim et al (2004) report that microbial transformation of smectite to illite occurred at ambient conditions within 14 days in laboratory experiments in which Fe(III)-rich smectite was incubated with *Shewanella oneidensis*. This transformation typically requires 4 to 5 months at a temperature of 300°C to 350°C and a pressure of 100 MPa in the absence of microbial activity (Kim *et al.*, 2004). Even in the absence of a smectite to illite transition, microbial reduction of Fe(III) to Fe(II) can reduce the swell potential in an iron rich swelling clay (Kostka *et al.*, 1996). These findings suggest that microbial processes may be used to mitigate swell potential in some expansive soils.

Biopolymers and Biofilms

A number of investigators have investigated the impact of biopolymers on saturated hydraulic conductivity with respect to the potential for forming hydraulic barriers, or bio-barriers, to contaminant transport. Khachatoorian *et al.* (2003) performed a series of permeability tests to evaluate "plugging" of fine sand by biopolymer slurry impregnation using five different biopolymers. The results of these tests demonstrated a permeability decrease of up to 14 orders of magnitude in less than two weeks. Biofilms form on a wide variety of surfaces, including living tissues, medical devices, industrial or potable water system piping, natural aquatic systems, soil particles, and geosynthetics. According to Donlan (2002), the solid-liquid interface between a surface and an aqueous medium provides an ideal environment for the attachment and growth of microorganisms. Many case histories of clogging of filters in dams, landfills, and water treatment plants due to growth of biofilms have been reported. For instance, in October 1985 an investigation was carried out to evaluate the reason for the clogging of the subsurface drains at the Ergo Tailings Dam (ETD) in South Africa. The aggregate and geotextile drains clogged only six months after they were put in service. Based on electron microscopy and X-ray diffraction analysis, it was concluded that the geotextile filter for the drains was clogged due to the growth of arsenic resistant microorganisms (Legge at al., 1985). The results of permeability tests on the clogged geotextile from the ETD subdrain revealed that the through-flow capacity was reduced by as much as an order of magnitude when compared to virgin geotextile.

Biopolymer and biofilm "clogging" of pore spaces may logically be inferred to be beneficial for various physical properties of soil besides permeability, including undrained shear strength, drained shear strength, and shear modulus. Furthermore, a significant reduction in permeability should significantly reduce, if not eliminate, the potential for earthquake-induced liquefaction. One concern with biopolymer and biofilm improvement is that it may not permanent, i.e. that the soil property changes may be reversible, requiring active maintenance of suitable environmental conditions. However, even if these property changes cannot be relied upon for the long term, there are many situations where "temporary" improvement of soils often is sufficient, e.g., stabilization and groundwater control for excavations and tunneling. In fact, in some situations the "reversibility" of the process may be a desirable trait (e.g., the use of biodegradable biopolymers for construction of permeable reactive barriers). Despite the potential benefits of biofilm and biopolymer accumulation, limited information has been reported on the impact of these phenomena on the shear strength, compressibility, or liquefaction potential of soil.

PREVIOUS RESEARCH RELEVANT TO THE MICROBIAL IMPROVEMENT OF THE PHYSICAL PROPERTIES OF SOILS

Mitchell and Santamarina (2005) published an overview on biological considerations in geotechnical engineering and discussed the interaction between microorganisms and geological processes. Mitchell and Santamarina (2005) highlighted that there are a limited number of studies of the effect of microbial activity on the shear strength and stiffness of soils. However, there are some data in the literature related to the effect of microbial activity on the hydraulic conductivity on soils. Most of the work that may be relevant to microbiological improvement of physical properties of soils (e.g., microbial mineral precipitation/plugging, biofilms, and biopolymers) is related to either bioremediation applications or to the efforts to enhance oil recovery from the petroleum reservoirs.

In addition to the work on the bioremediation of hydrocarbons discussed previously, several researchers have studied the feasibility of capturing inorganic contaminants through mineral precipitation and containment of contaminated groundwater using biobarriers. For example, Warren *et al.* (2001) studied solid phase capture of Uranium Dioxide (UO_2), Strontium (Sr), and Copper (Cu) through biomineralization (i.e., direct or indirect formation of insoluble precipitates by microorganism) in the laboratory and concluded that calcium carbonate precipitation promoted by bacterial hydrolysis of urea was an effective method of capturing Sr. Cunningham *et al.* (1991) performed a series of laboratory tests to assess the effect of biofilm accumulation on porous media hydrodynamics and found that the intrinsic permeability of different sizes of glass spheres and sands decreased by up to 98 percent, stabilizing at 1 to 5 percent of the original value (i.e., the value with no biofilm) within a few days. Komlos *et al.* (1998) performed laboratory experiments to examine the effects of thick biofilms in porous media under radial flow conditions using *Pseudomonas fluorescens*, facultative anaerobic bacteria capable of denitrification. Through bacterial inoculation and nutrient addition, Komlos *et al.* (1998) reported the formation of a biobarrier that resulted in a decrease in horizontal hydraulic conductivity of the porous media from 6.7×10^{-2} cm/s to 1.7×10^{-2} cm/s (a 75 percent reduction) over 24 hours. Dutta *et al.* (2005) built an in-situ biobarrier at a site near Albuquerque, NM, and stimulated the indigenous bacteria to contain and remediate groundwater contaminated by nitrate through denitrification. Even though the biobarrier did not completely halt the flow of contaminants, the reduction in the hydraulic conductivity of the subsoils resulted in a formation of an active treatment zone and nitrate concentrations dropped from 275 mg/L to less than maximum contaminant level (MCL) for safe drinking water of 10 mg/L over a period of approximately 300 days. Dutta *et al.*

(2005) also reported problems with biofouling around the well screens used to monitor this process within four months from the start of the field study.

The oil industry has been interested in microbiological mechanisms that result in plugging of geological formations in order to reduce the hydraulic conductivity of the layers surrounding oil bearing strata and to improve the efficiency of oil extraction. A series of laboratory tests were conducted at the University of Calgary, Canada, to evaluate the plugging of sintered glass bead cores using vegetative and starved bacteria by MacLeod *et al.* (1988). The results of the experiments indicated, under the same injection conditions (500 pore volumes of *Klebsiella pneumoniae s*uspension), bacteria starved for 2 weeks reduced core permeability by 71 percent whereas the use of vegetative cultures resulted in a reduction in core permeability by 99 percent. MacLeod *et al.* (1988) also concluded that, while the vegetative cultures were somewhat more effective at plugging in the short term, the general starvation of the bacterial cultures prior to core injection can improve penetration and may provide a new bacterial plugging technique for petroleum reservoirs based on the data of respiratory activity and Deoxyribonucleic Acid (DNA) – derived cell density with respect to core depth.

Research on the impact of biopolymers on the geotechnical properties of compacted soils was conducted by Karimi (1998). Karimi (1998) performed hydraulic conductivity and triaxial shear strength tests on compacted specimens of Bonnie silt mixed with xanthan gum, a commercially available biopolymer. The results of permeability tests indicated that the hydraulic conductivity of Bonnie silt was reduced by two orders of magnitude when mixed with 0.3 percent xanthan gum by weight at a water content greater than the optimum moisture content of the silt and that this effect lasted for at least six months (Martin *et al.*, 1996). The shear strength of the compacted Bonnie silt mixed with 0.3 percent xanthan gum by weight was also improved (up to 30 percent increase in consolidated-undrained (CU) triaxial tests) (Fig. 1). Figure 1 indicates that the maximum deviatoric stress reaches a constant value approximately 20 days after hydration of the compacted silt mixed with xanthan gum. Note that "gum 1%" solution in Fig.1 corresponds to a xanthan gum content of 0.3 percent by weight (Karimi, 1998).

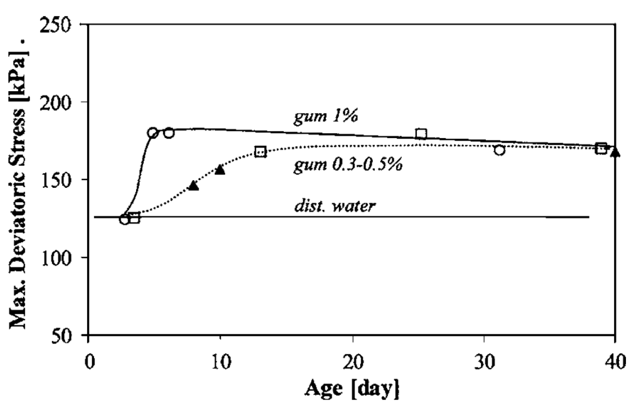

Fig. 1. CU Triaxial shear strength tests on compacted Bonnie silt mixed with xanthan gum (Martin et. al, 1996)

Perkins *et al.* (2000) performed triaxial shear strength tests on dense Ottawa Sand specimens to evaluate the effect of biofilms on the shearing properties of granular soils. *Klebsiella oxytaca* was introduced into the soil specimen with a nutrient solution. Perkins *et al.* (2000) used ultra-micro-bacteria (UMB) (i.e., vegetative cells that shrink and revert to a low metabolic rate when subjected to starvation) to ensure homogeneous distribution of microorganisms. The growth of the biofilm was facilitated via periodic flow of a nutrient solution through the sample prior to the application of loading. Perkins *et al.* (2000) concluded that the biofilm had a negligible influence on the shear strength and stiffness of the Ottawa sand based on CU and consolidated-drained (CD) triaxial tests (Fig. 2a) but that it increased the creep deformation (Fig. 2b). The "average creep slope" plotted in Fig. 2b represents the average of the slope of the vertical strain vs. log-time curves from two secondary compression experiments. Furthermore, Perkins *et al.* (2000) reported that the hydraulic conductivity of the sand was reduced by an order of magnitude by the biofilm. Although Perkins *et al.* (2000) performed direct and plate counts to evaluate the population of the microorganisms at the end of the laboratory experiments, no data were provided on the distribution of biofilm throughout the sample (e.g. images from scanning electron microscopy, SEM).

Cabalar and Canakci (2005) performed a series of laboratory tests on sand mixed with different ratios of xanthan gum. Cabalar and Canakci (2005) state that direct shear tests showed an increase in "average shear strength at failure" from 30 kPa to 190 kPa when the xanthan gum content of the sample was increased from 1 percent to 5 percent. However, neither the normal stress nor load-deformation data were provided by Cabalar and Canakci (2005). Furthermore, because no data were provided on the baseline shearing strength of the sand (i.e., the shear strength of the sand with no xanthan gum), there is no way to assess whether the addition of xantham gum initially resulted in an increase or decrease in shear strength.

Researchers at the Delft University of Technology and GeoDelft Institute (GeoDelft) in the Netherlands have also been studying improvement of soil properties using microbiological processes. The two processes that are being studied at GeoDelft are biogrout, an in-situ cementation process controlled by microorganisms that degrade urea, and bioseal, a sealing process which locates and seals leaks in water retaining soil/fractured rock layers. Research work initially carried out by Whiffin (2004) at Murdoch University in Western Australia led to development of the GeoDelft biogrout testing program. Whiffin (2004) studied the effects of microbial precipitation of calcium carbonate through hydrolysis of urea on the physical properties of sands.

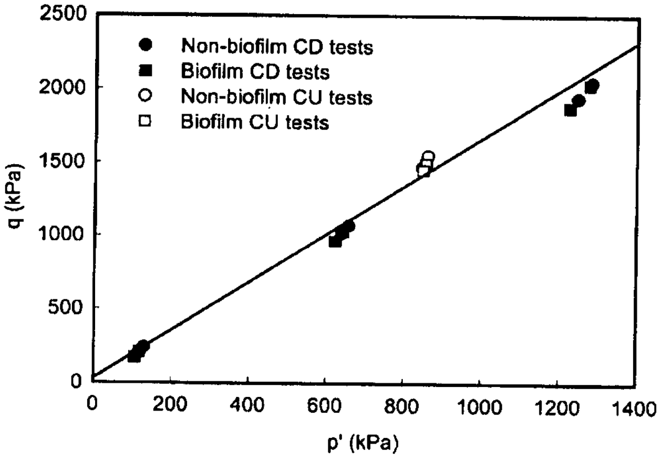

Fig. 2a. Shear strength envelope from CU and CD Triaxial (Perkins et al., 2000)

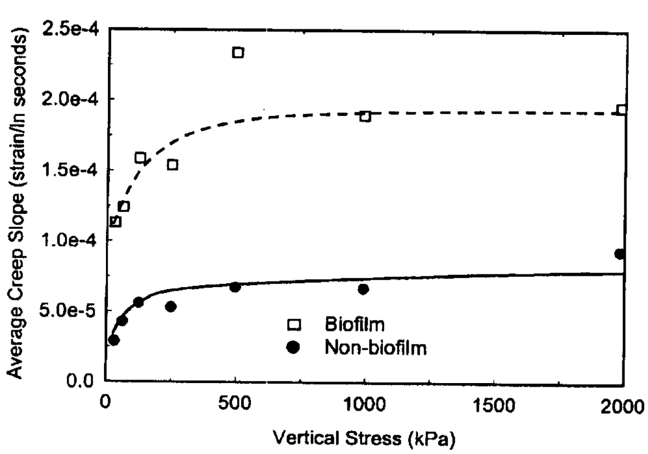

Fig. 2b. Secondary compression experiments on Ottowa sand (Perkins et al., 2000)

An aerated solution of urea, calcium, and urea-hydrolyzing bacteria was injected into sand specimens to induce calcium carbonate precipitation (Fig. 3). The change in physical properties due to microbial calcium carbonate precipitation was initially evaluated by Whiffin using P-wave velocity measurements that were assumed to be correlated with uniaxial compressive strength. The P-wave measurements indicated an increase in cementation and shear strength with increasing concentration of hydrolyzed urea (Whiffin, 2004). Whiffin (2004), then, performed triaxial shear strength tests on Dutch Koolschhijn sand injected with urea, calcium, and urea-hydrolyzing bacteria and reported that shear strength increased by a factor of 8 and stiffness increased by a factor of 3, without a significant change in pore volume. However, important details of the triaxial tests, e.g., the confining pressures, and drainage conditions, were not reported.

GeoDelft's biosealing process involves a consortium of microorganisms that form a bioslime and an insoluble iron sulfide (FeS) precipitate that accumulate around a leak. While the biogrouting work reported by GeoDelft involves only

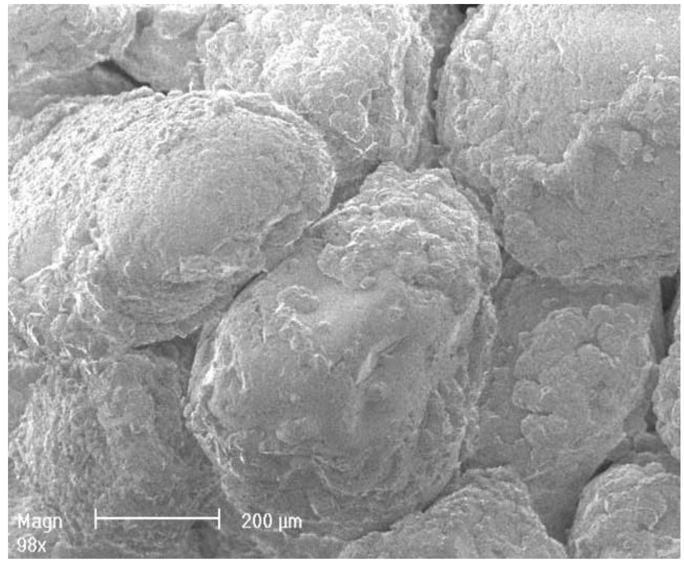

Fig. 3. Scanning electron micrographs of <600 µm silica sand (Whiffin, 2004)

bench-scale laboratory tests, GeoDelft's biosealing technology has actually been tested in the field in 2004 and was used on a major infrastructure project in 2005, construction of the Aquaduct Ringvaart Haarlemmermeer, a part of the high-speed rail link (GeoDelft, 2006).

Recently, DeJong *et al.* (2006) evaluated the effects of calcium carbonate precipitation induced microbially through urea hydrolysis on the shearing properties of loose sands. Shear wave velocity measurements were employed by DeJong *et al.* (2006) to monitor the development of cementation during microbial treatment (a period of approximately 24 hours) and consolidated undrained triaxial shear tests were performed at the end of the treatment period. DeJong *et al.* (2006) observed an increase in shear wave velocity from approximately 200 m/s to 540 m/s due to microbial treatment and reported that the microbially cemented soils displayed a similar shearing response to gypsum cemented soils under undrained conditions (Fig. 4). DeJong *et al.* (2006) concluded that pH, oxygen supply, metabolic status and concentration of microorganisms, and calcium concentration are critical factors for the success of this application.

POTENTIAL ENGINEERING APPLICATIONS OF MICROBIAL SOIL IMPROVEMENT

Remediation of soil liquefaction through induced precipitation, mitigation of soil swell (expansion) potential through mineral transformation, and groundwater control through microbial mineral precipitation or biofilm development are among the potential beneficial applications of microbial processes to geotechnical engineering. The applicability of microbiological processes to these soil improvement problems logically depend on a number of

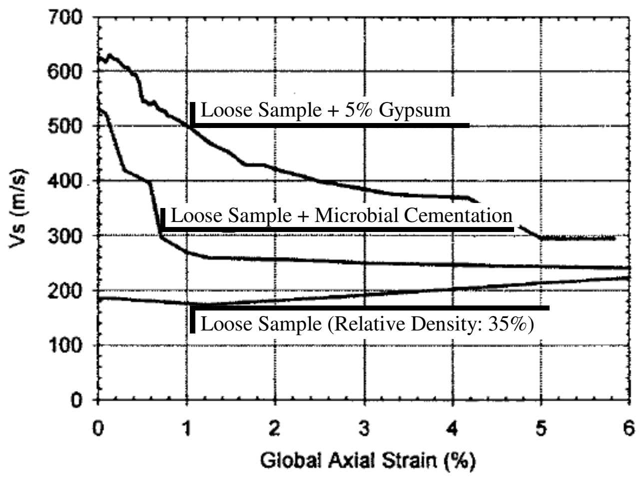

Fig. 4. Shear wave velocity measured during monotonic triaxial tests (DeJong, 2006)

variables, including the type of microbial metabolism involved in the process, interactions with other microbes present in the environment, soil type, available nutrients, pH, temperature, pressure, concentration of ions, and the availability of oxygen and other oxidants.

Application to Remediation of Liquefaction Potential

Many of the current technologies to improve the behavior of soils susceptible to earthquake-induced liquefaction result in large ground deformations, making them unsuitable for use in developed areas. Furthermore, techniques suitable for use in developed areas, e.g. compaction grouting, generally incur high costs. Microbially-induced mineral precipitation offers the potential for significant improvement in liquefaction resistance due to development of intergranular cementation with little to no ground deformation. The optimal microbial precipitation mechanism for a given site likely depends upon the characteristics of the subsurface environment. For instance, if an anaerobic subsurface environment with high sulfate concentration is encountered, sulfate reducing microorganisms, e.g. *Desulfovibrio desulfuricans*, with an appropriate nutrient solution (and salts, if needed) can be introduced to the ground through wells screened along the breadth of the potentially liquefiable layers. Other potential mechanisms, depending on the site conditions, include the introduction of *Bacillus pasteurii* or *Pseudomonas denitrificans* if calcium carbonate precipitation through ureolysis or denitrification, respectively, are the desired mechanisms. Potentially liquefiable sand deposits near and/or along the shores of water bodies, a common situation along the west coast of the US and many other liquefaction-prone areas, may be a particularly suitable environment for microbial precipitation because of the presence of dissolved minerals in the pore fluid and/or anaerobic conditions.

Application to Swelling Soils

While most work to date on use of microbial processes for soil improvement have focused on granular soils, the mitigation of swelling (expansive) soils is one area where microbial processes may improve the performance of fine grained soils. Estimates of the total cost of damage due to swelling soils, one of the least publicized geologic hazards, were estimated at $2 to $7 billion in the U.S. in 1987 (Jones and Jones, 1987) and may reasonably be considered to be at least twice as much today. Currently, pre-wetting of the site and ex-situ lime treatment of these soils are among the most common geotechnical approaches used to mitigate the potential for swell in a fine grained soil, along with expensive structural measures such as post-tensioning of foundation slabs. In iron-rich expansive soils, promoting iron-reducing microbial activity to reduce Fe(III) to Fe(II) and possibly transform smectite to illite may provide an alternative solution to mitigating swell (expansion) potential of soils and could provide significant advantages over the existing remedies in terms of both cost and environmental impact.

Similar to lime improvement, microbial improvement of fine grained soil can is likely to be initially applied ex situ. Nutrients and salts containing potassium can be added to stockpiled soil to stimulate the iron-reducing microorganisms. The nutrients and salts can be introduced in solution to promote their distribution through the soil. As suction draws the pre-wetting solution into the soil, it will carry the required nutrients and cations with it. In the absence of indigenous iron-reducing microbial metabolic activity, the soil could be augmented with *Shewanella oneidensis* or some other iron-reducing microorganism to the site along with a source of nutrient. The in-situ application of this technology may be limited due to the size of the bacteria relative to the pore size of fine grained soils, which may limit the ability of the bacteria to penetrate the soil (Fig 5).

Application to Groundwater Control

Groundwater control in coarse grained and stratified soils has long been a challenging task for geotechnical engineers. Because of the difficulties in identifying the geologic microstructures that may cause serious groundwater control problems, high costs and large factors of safety are generally associated with the groundwater control solutions for excavation and tunneling. However, as noted previously, clogging of the drainage layers in landfills, at mines, in water treatment plants, and in dams has been attributed to microbial activity and the resulting biofilms and/or microbially precipitated minerals. This observation suggests that one of the microbial mineral precipitation mechanisms or a mechanism that employs microorganisms that develop biopolymers and biofilms can be used to reduce the hydraulic conductivity of soil.

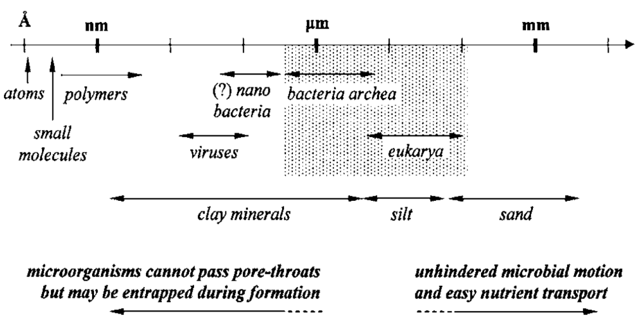

Fig. 5. Comparative sizes of microorganisms and soil particles (Mitchell and Santamarina, 2005)

If groundwater control is achieved through microbial mineral precipitation, then a long-term solution may be achieved. On the other hand, biofilm and biopolymer production may be suitable for interim (short term) groundwater control, e.g., for control of groundwater in a temporary excavation below groundwater table. It is possible that biofilm or biopolymer production may be stimulated simply through introduction of suitable microorganisms and/or nutrients in solution. This technology could also be used as part of barriers for waste containment applications.

SUMMARY

Mechanisms by which microorganisms play a role in geological phenomena, along with observations of certain "adverse" effects of microorganisms on engineered facilities, suggest that in the proper context microorganisms can be used to improve the mechanical properties of soils for engineering purposes. These mechanisms, including mineral precipitation, mineral transformation, biopolymer growth and biofilm formation, have a variety of potential engineering applications, including enhancing soil stability, improving foundation performance, and control of groundwater. Remediation of soil liquefaction through microbial carbonate precipitation, mitigation of soil swell (expansion) potential through biological mineral transformation, and groundwater control through microbial mineral precipitation or biofilm development are among the potential beneficial applications of microbiology to geotechnical engineering.

The applicability of microbiological processes to soil improvement will likely depend on a variety of factors, including the type of microbial metabolism desired, interactions with other microbes present in the environment, soil type, available nutrients, depth below ground surface, pH, temperature, pressure, concentration of ions, and the availability of oxygen and other oxidants. Current research at Arizona State University includes performing bench-scale experiments to establish candidate technologies for each mechanism and ultimately conducting field tests for mechanisms that look promising based upon the bench scale experiments. The authors hope that interdisciplinary research efforts carried out by microbiologists, chemists, geologists, and geotechnical engineers, collaboratively, will result in realization of the potential for microbiological soil improvement technologies.

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